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Assessment of Methodologies for High-Frequency, Fine-Scaled, Spatially Referenced In Situ Data Collection and Analysis

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Preface

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1   Introduction

Background

Advances in analytical ability and measurement instrumentation form the two major elements of recent technological progress in limnology, aquatic ecology, and water quality monitoring and assessment. These two elements have historically accompanied and occasionally preceded conceptual advancement. Recently, both scientists and managers have recognized the need for applications at spatial scales much finer than traditional methods have allowed in the past.

Examination of small-scale temporal and spatial patterns has long been an academic goal for identifying the existence or importance of specific ecological and biological processes. Limnologists studying reservoirs, for example, implicitly recognized the existence of such trends by designating zones in which different processes dominated those environments. For example, a major inflow to a reservoir results in the establishment of longitudinal gradients, which have often been characterized as zones (riverine, transition, and limnetic from headwater to dam (Thornton et al. 1980)). Such zones are recognized to be somewhat arbitrary and quite variable in time and space. Designation of these zones was important because it demonstrated a conceptual recognition of great ecological variability throughout reservoirs. Furthermore, the selection of three zones is admittedly a substitute for what in reality is a vast continuum of limnological and ecological processes. What was missing was the ability to extend observation to such a conceptualization.

A good example of the difference is a comparison between the relatively numerous, small natural lakes and relatively uncommon, larger reservoirs. In the United States, most such natural lakes have been created by glaciation (in north temperate regions), solution of bedrock (in karst regions such as Florida), or as the outcome of river meanders or tectonic processes elsewhere. Most of these natural processes yielded lakes of relatively simple shape with the deepest region near the lake center. Many of these natural lakes can be characterized using a single sampling location in the deepest region. In larger natural lakes with more than one embayment, the characterization may require a sampling location in more than one deep region.

For smaller reservoirs with simple shapes and few inflows, a single location may also be used to characterize water quality.

In current practice, for relatively small, simple lakes and reservoirs, limnological studies traditionally involve the collection of water samples or in situ measurements at discrete depths at a limited number of sampling locations assumed to be representative of regions of a lake or reservoir. Large aquatic systems, natural or artificial, demand more sampling locations, sometimes selected using statistical design criteria (Thornton et al. 1982; Gaugush 1986, 1987). Regardless of approach followed, there is an implicit assumption that each sample location characterizes a region of the reservoir whose extent is limited by half the distance to the next sample location, often on the scale of kilometers.

Large systems or smaller systems that have great complexity and strong spatial gradients pose the greatest challenges for characterization of water quality or ecological processes. In such complex systems, traditional methods are limited in their ability to characterize the lakes, and studies usually address narrow, well-defined questions amenable to the available observational methods. This is an entirely proper way to proceed to answer such narrow questions. For example, simple prediction of outflow quality using the simple model SELECT requires information only for one location adjacent to the dam intakes. Questions of long-term change may employ any single location that has been monitored over a sufficient time. But the larger questions of spatial heterogeneity in multiple dimensions remain unaddressed or poorly addressed with conventional methods.

Because important differences in water quality can occur over relatively short vertical and horizontal distances (e.g., Kennedy, Thornton, and Gunkel 1982), any effective means of increasing the spatial and temporal resolution of sampling will greatly enhance the assessment of reservoir water quality or ecosystem processes. Moreover, the development of modeling approaches employing multiple dimensions demands multidimensional sampling and assessment for model support and verification. For large reservoirs with multiple significant inflows, the emerging importance of land use and loading (i.e., total maximum daily loads) will require increased emphasis on variability among embayments and their tributaries within reservoirs. Single characterizations of such complex reservoirs will become increasingly difficult without appropriate data acquisition methods.

Monitoring equipment has already been developed that can adequately address temporal variability through the incorporation of rapid data logging and automation. Only in extreme situations does the temporal variability exceed the instrument capability to record that variability accurately. This is true in spite of the fact that (except for a few refinements) sensor technology has remained essentially unchanged for several decades. New technology has contributed mostly increased reliability, stability, and ease of use.

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Until recently, conventional sensor technology could address spatial variability only in a limited manner—limited by spatial scale or the time needed to gather information. Newly available instrumentation now enables rapid three-dimensional assessment of water quality based on any available traditional water quality parameters. These instruments consist of programmable towed platforms that enable a measurement sonde to interrogate a large number of depths and locations over a short time.

Purpose and Scope

Technological advances in instrumentation now offer new opportunities for the collection of fine-scale, spatially explicit water quality data for lakes, reservoirs, and rivers. This report describes practical considerations for developing and applying strategies employing Global Positioning Systems (GPS), multiparameter sondes, and towed submersible vehicles. Equipment and sample design approaches are demonstrated based on example applications.

In theory such technology should supply data needs that result from the large questions. For limited parameters at this time, the technology does provide that needed capability. However, transition from conventional technology to this spatially and temporally intensive application exceeds the capacity of some of the conventional technology to respond adequately. This report details both the advantages and the limitations of such transitions.

2 Methodological Approaches

Current Technology

As new methods and technology are developed and as new conceptual approaches to the assessment and management of aquatic resources are discovered, the best of the standard methods often remain, complementing the newer methods and approaches. Methods that have achieved accuracy and reliability are robust and can be replaced only by other methods that achieve higher standards. For this reason, a survey of currently employed methods may include elements representing a historical progression of both technology and concept. For example, the individual spot observation using primitive tools such as thermometers and microscopes survives because this method optimally fills a particular need. Today needs have expanded to include rapid water quality observation and assessment in three spatial dimensions as well as time. The sequence of development of technology to meet those needs is instructive to determine both the direction and success of current invention.

The most common sampling approach for field monitoring and assessment employs spot measurements at preestablished locations. These may be employed at one or many depths depending on data needs. Such applications are manifested in three ways. First, simple one-time surveys on which more sophisticated designs are based employ manual data collection at locations, times, and frequencies that are variable and somewhat arbitrary. The results of such efforts may be used to design subsequent efforts that address specific questions and data needs. The second, related approach incorporates regular manual measurements at one or more depths for a specific purpose or for establishment of unknown long-term trends. This second approach may incorporate other technology such as continuous remote monitoring as well. The third approach involves frequent manual surveys at multiple depths and locations along rivers and in reservoirs. The three approaches obviously represent increased investments of labor and time as well as hardware.

As mentioned previously, technology has allowed incorporation of unattended remote monitoring at fixed locations. This technology is very robust if installed for a single in-line site or at a single depth. The data acquisition and telemetry technology has surpassed the sensor technology in its ability to respond rapidly to changing conditions and in its flexibility of application. Electronic data technology has also surpassed the ability of conventional sensors to vary location remotely in an automated manner. Although several attempts to address spatial variation remotely in the depth dimension have been made, and although commercial automated solutions exist for limited applications, the solutions remain expensive and limited in applicability. Although they have good potential, they are not yet robust in their application. Conventional manual methods remain competitive and, for many applications, superior.

Where the first data gathering approach, simple spot sampling at single locations, is well known by all who do routine limnological surveys, application of the second approach is still being expanded in the field. An example of the second approach can be seen in Figure 1, a week-long measurement of chlorophyll fluorescence at a single location and depth in Richard B. Russell Lake, South Carolina and Georgia. The continuous, 5-sec-interval fluorescence measurements show the diel variability of an important limnological parameter at a single depth, 1 m. As shown in
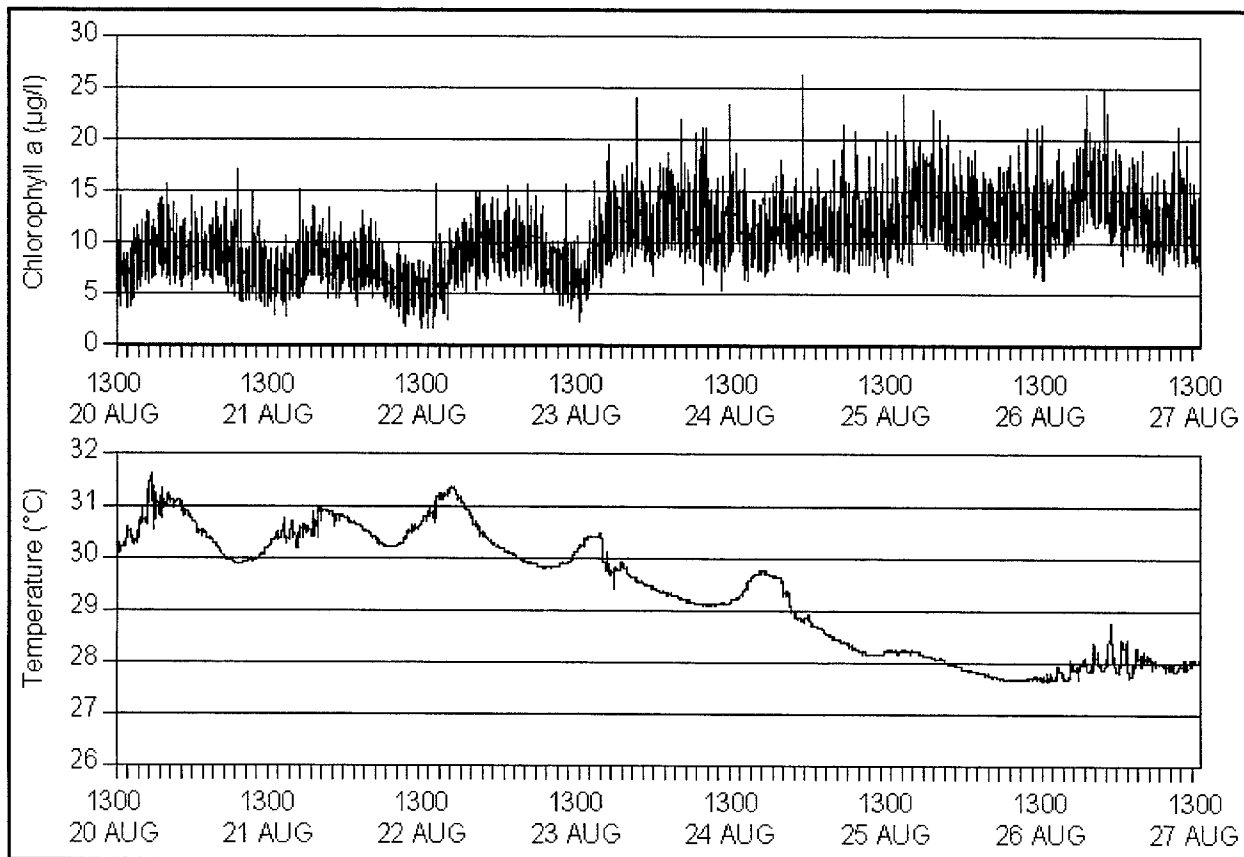

Figure 1.   Variation of temperature and chlorophyll a fluorescence over 7 days at sta 130 and a depth of 1 m. This shows diel variation of both parameters as measured at 5-sec intervals

Figure 1, on a diel basis chlorophyll varies approximately 10 mg m^{-3}. This variation can have the effect of more than doubling the chlorophyll concentration through the diel period. A real variation of more than 100 percent is important because it corresponds to large diel changes in trophic status as measured in popular conventional indices (Carlson 1977). It also poses a challenge to sampling design as well as to interpretation of results.

The ability to describe and monitor such important temporal changes easily results from comparatively recent improvements in one specialized measurement technology: miniaturization of optical fluorescence measurement. Coupled with improved data collection and management, the ability to measure chlorophyll fluorescence rapidly and accurately in situ challenged the conceptual idea of trophic status that is also a comparatively recent development.

In this example of the second approach, a small refinement in technology provided the basis not only for a challenge to a popular limnological characterization, but also for the formulation of two new alternative hypotheses regarding diel phytoplankton distributions. Either the observed diel chlorophyll variation is due to motility and control of vertical position, or the variation is due to diel water movements. Resolution of such questions is beyond the scope of this report. However, the exercise is a clear demonstration of the potential conceptual gains from modest improvements in systematic automated monitoring at a fixed site.

The third approach, employing labor-intensive manual surveys at fixed locations, is still the most common approach to field data collection. This robust approach will continue to be the standard for conventional monitoring and assessment studies until the need for more intensive data collection demands the increased resources necessary for such an increase of effort. Advantages of this approach include flexibility of design, ability to make field-based decisions and changes in sampling, immediate access to data, relatively low cost, and, with attention to quality control, great accuracy and reliability for the data.

However, manual sampling at multiple locations at infrequent intervals has reached the apogee of its contribution to the understanding of lake processes and aquatic ecology. Although the approach will continue to be employed, important questions regarding water quality distributions in spatially complex systems increasingly demand data intensity that eclipses the abilities of most manual survey methods. New approaches are available, but these have limitations in applicability that require precautions prior to adoption.

Towed Vehicle Applications

While electronic design has enabled rapid, automated data collection, thus filling part of the need to address temporal variability, other engineering solutions have addressed the need for rapid assessment of large spatial regions of aquatic systems. The most prominent of these is a towable platform measuring a suite of water quality parameters in situ throughout multiple depths and over extensive areas in a short time.

Two advances were necessary for this approach to work reliably. The first was the development of accurate positioning technology, the most prominent of which is the GPS. Using GPS and rapid measurement of surface water quality, a growing number of systems have been studied successfully for fine-scale variations of water quality in two dimensions. Three examples of this include studies in Laguna San Jose, Puerto Rico (Kennedy, Fernandez, and Abreu 1996), West Point Lake, Georgia (Kennedy et al. 1994), and the Kanawha River, West Virginia.[1]

During studies at West Point Lake, field measurements were made to provide ground truth for the interpretation of results from LANDSAT images. In that study, multiparameter sondes were used to collect data at many locations in a short time. Multiple watercraft and field crews were deployed to make the necessary field observations. At the same time, surface water samples were taken for later analysis of chlorophyll a. In that early study, position was determined for each sample location using existing known navigation buoys. In one part of the study effort, field measurements were made and samples were taken from predetermined sites corresponding to the navigation buoys. In a separate effort, the GPS position was determined for each of the same buoys. The GPS data were postprocessed using data from a community base station to remove the positional error. The two data sets were subsequently combined, associating the field data with the position data. The final data set was combined with laboratory analyses of chlorophyll a to provide the needed ground truth for interpretation of the LANDSAT data. This early study was the most basic application of existing technology to spatially complex trends. Its limitations included the need for intensive labor as well as a substantial time investment to complete the observations. It addressed only variation of lake water quality at the water surface.

Studies on Laguna San Jose (Kennedy, Fernandez, and Abreu 1996) improved on the effort for West Point Lake by incorporating logged position data as well as water quality data. The field effort employed GPS position coupled with continuously logged water quality and chlorophyll fluorescence data. Figure 2 diagrams the water flow and setup for the data collection platform for spatially referenced surface water surveys such as performed on Laguna San Jose. The GPS and water quality instruments are interfaced with a data logger, and water from the moving vessel is

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[1] R. H. Kennedy, Personal Communication, Environmental Laboratory.

Flow-thru Monitoring System Schematic   rmm 981001
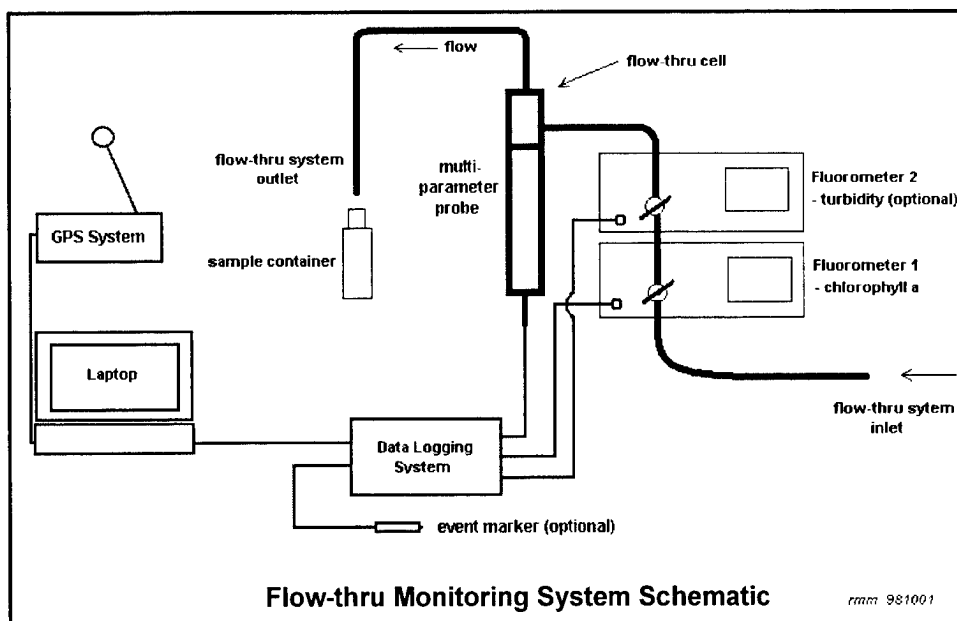
Figure 2.   Diagram of a generalized flow-through system for collecting
geographically referenced water quality data onboard a moving vessel.
The system consists of a flow inlet mounted below the waterline, a
series of flow-through sensor systems, a sample collection port, a
GPS system logged to a computer, and data inputs to the computer
from the sensor arrays.

delivered to flow-through cells for measurements. This system is robust for
measurement of surface conditions and has the added advantage of protect-
ing the instrumentation from damage or loss. In the study at Laguna San
Jose and similar studies, water samples were also collected to provide base-
line measurements of chlorophyll a.

For Laguna San Jose, depth trends were not as important because the
entire water body was relatively shallow. Surface characterization of water
quality was sufficient. Figure 3 illustrates results of the study at Laguna
San Jose. In the figure, the sampling track is shown as well as the resulting
map of surface chlorophyll. Improvements over the study at West Point
Lake included continuously logged position and continuously logged water
quality data. These improvements not only made data handling more con-
venient but also allowed greater data density and a more precise interpreta-
tion of spatial trends.

The limitations of the studies on Laguna San Jose, however, were simi-
lar to those of the investigation at West Point Lake. Although the instru-
mentation was better able to incorporate positional and water quality
parameters at the same time, the results were not fully accessible until proc-
essed at a time well after the field work. This limitation was due, in part, to
the instrumentation that, although improved, was still clumsy in operation
and data handling. Considerable time and labor were invested in acquisi-
tion of that data, and the major advance over the approach at West Point
Lake was that positional and water quality data were collected
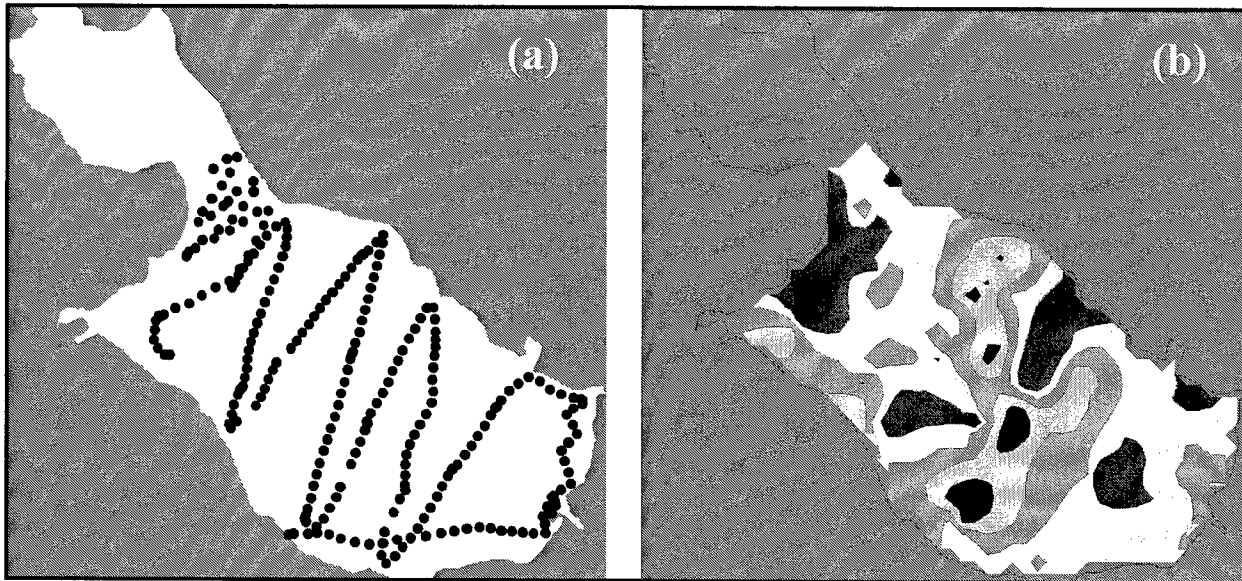
Figure 3. Maps of Laguna San Jose, Puerto Rico, showing the sampling track (a) and the resulting map of surface chlorophyll distribution (b). This demonstrates the real spatial variation possible for even relatively small aquatic systems

simultaneously without the need for fixed sampling positions. In Figure 3 the sampling track represents a large amount of rapidly acquired data whereas in West Point Lake, those data were confined to a relatively small number of individual fixed locations.

Where the water body is very shallow, as in Laguna San Jose, or well-mixed, surface spatial studies can be appropriate. In a study on the Kanawha River (Kennedy, Meyer, and Cremeans 1999), a new level of sophistication was attained during rapid measurements throughout a reach of the river. This investigation employed a surface water intake mounted on a watercraft and collected continuous water quality and position data. This approach was used to describe trends throughout that reach of the river. Figure 4 illustrates the sampling track for that study. The only expected gradient for this study was longitudinal to the river channel. Therefore, for this application the sampling design and configuration were fairly complete.

In an earlier effort by the U.S. Army Engineer District, Huntington, in July 1991, temperature and dissolved oxygen data were collected rapidly during a survey of 497 km (309 miles) of the Ohio River. Figure 5 displays data taken during that effort. That study demonstrated that conventional methods have been adaptable to large-scale one-dimensional spatial surveys for nearly a decade. However, limitations were posed by the approach as well as the sensor technology. In Figure 5, there was obvious success in identifying several important small-scale thermal impacts to the river. However, where dissolved oxygen trends were clear over long distances, the ability of this sensor to rapidly track quickly changing conditions was limited. The stepped appearance of the data for dissolved oxygen was, in part,
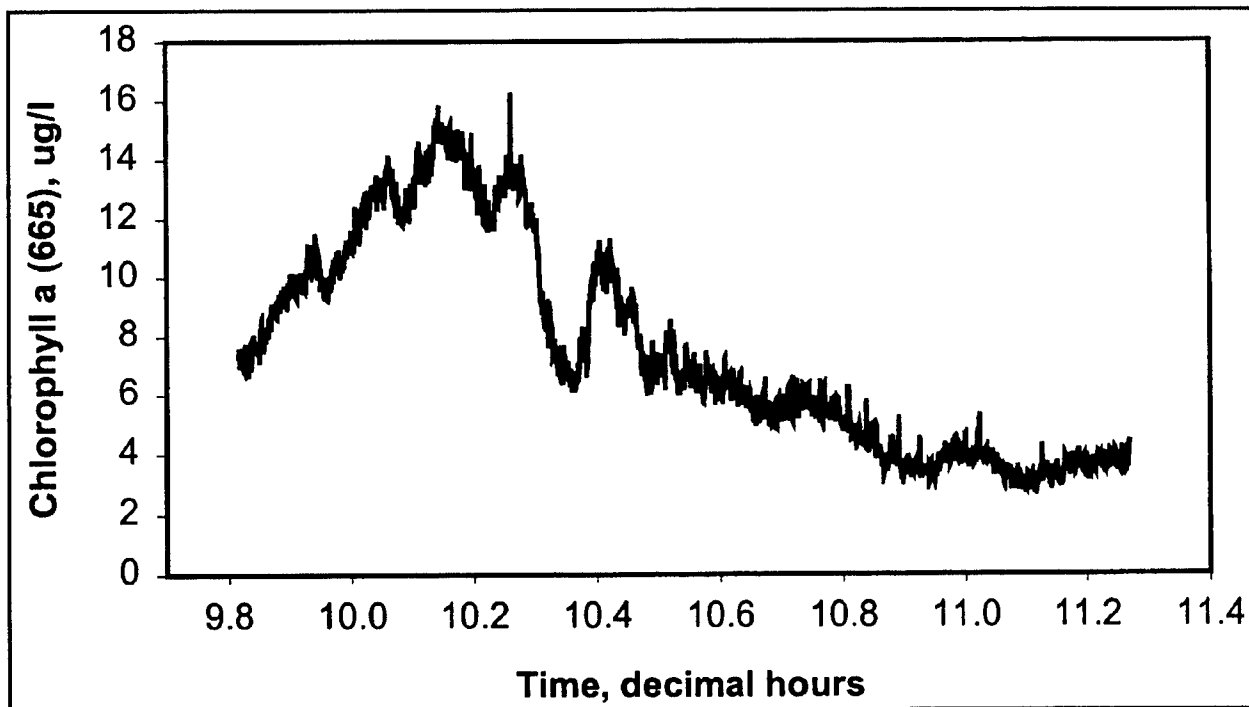
Figure 4.   Variation of chlorophyll a throughout an extensive reach of the Kanawha River. In this plot, travel velocity was relatively constant and time may be loosely interpreted in terms of distance. The substantial variation observed in this study may not have been discovered using conventional methods. Using this approach, the only limitation to the distance traveled during one day was the speed of the watercraft and the data interval required by study goals
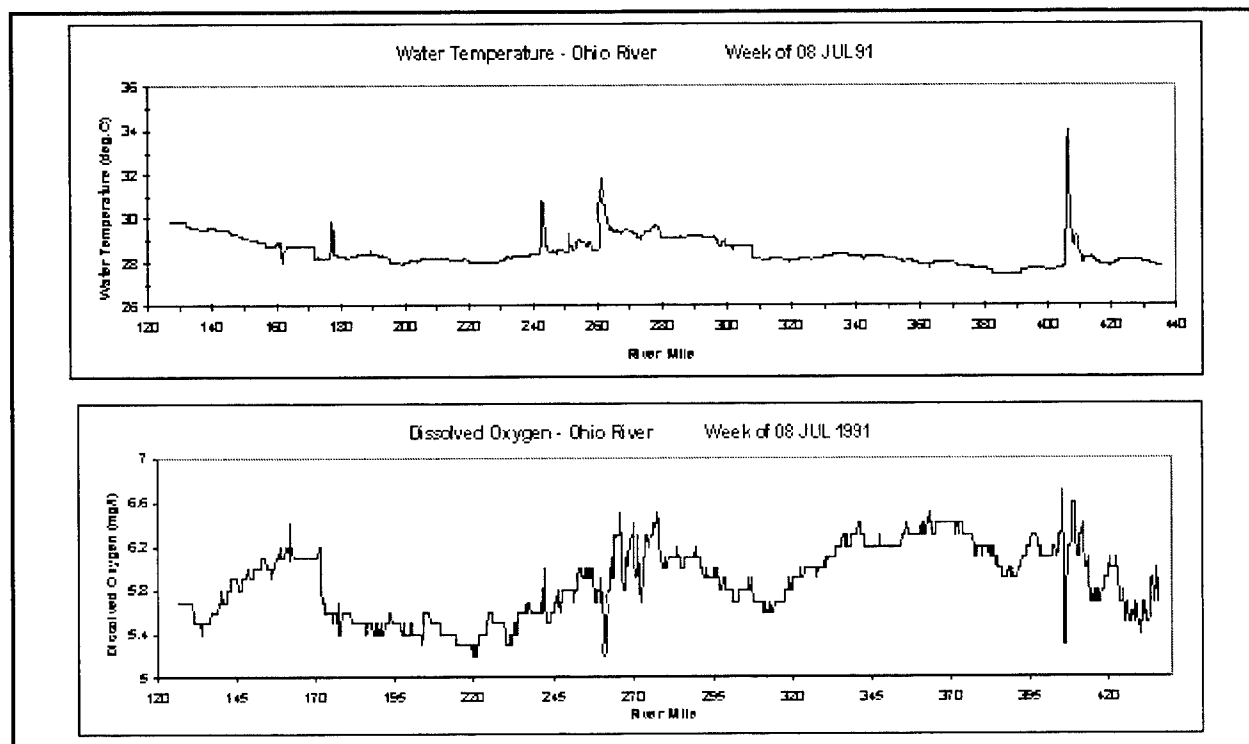
Figure 5.   Changes in water temperature and dissolved oxygen concentration along a 497-km (309-mile) reach of the Ohio River

Chapter 2   Methodological Approaches

due to the length of time necessary for the sensor to "read" at each new time and position. Its slow response posed a limit then as well as now.

The study on the Kanawha River employed improved technology allowing immediate access to field data for visualization and analysis. The water quality and positional data were automatically associated with each other, and access to the results was quick. However, although technology had matured, and data management was superior, this approach remained limited to investigation of surface conditions only. Where appropriate, this method proved superior to previous methods. Large, deep reservoirs with gradients in three dimensions were still nearly intractable.

In most of these early efforts and in similar ones, the common components to the design were the equipment and the study goals. The design always maximized the spatial coverage of the sampling while time of sampling was minimized. Equipment always consisted of adequate watercraft with water sampling, flow-through systems, continuously reading water quality sondes, and continuously recorded GPS positions. The study goals were always confined solely to that limited capability offered by the equipment and design—investigation of surface water quality spatial variability. Rapid assessment of water quality at depth has remained an elusive goal.

3 Technological Solution to Three-Dimensional Data Needs

Instrumentation that enables rapid three-dimensional assessment of water quality is now available in a configuration that can be applied in reservoirs. These instruments consist of programmable towed vehicles that, when equipped with a water quality measurement sonde, enable investigators to interrogate a large number of depths and locations over a short period of time.

In principle, their design is simple and consists of a controllable dive plane coupled with a platform that can carry a multiparameter measurement sonde. This assembly is then tethered from a conventional watercraft and towed through areas of interest.

These towed platforms have been employed in marine environments (e.g., Rudnick and Ferrari 1999; Creed, Glenn, and Chant 1998; Barth 1997) where they were developed for data needs similar to those identified for fresh waters. Marine versions are large and heavy, and usually require substantial physical surface support. Instruments developed for marine systems have not, as a rule, been easily adapted for reservoir applications. However, recently new versions of these towed platforms have been developed that can be applied in reservoir systems. These are capable of deployment from many types of watercraft and can be automated for operation or operated manually.

This new capability greatly increases the opportunity to describe water quality variation and distribution in highly variable freshwater systems. At the same time, it diminishes the potential error associated with discrete sampling. The ability to gather fine-scale data in three dimensions is an undeniable improvement in water quality monitoring, but this new technology also has limitations and specific requirements for application.

Instrumentation Design and Field Application

Most towed platforms capable of automated operation and data gathering have similar design features. These include a structure in which to house measurement instrumentation, a moveable dive plane allowing control and variation of vertical position in the water column, and additional stabilizing fins to control the motion of the platform as it is towed through the water. Also required is a means of data acquisition and management.

Figure 6 illustrates the MiniBAT® (manufactured by Guildline Instruments, Inc., Lake Mary, FL), the towed vehicle employed in this demonstration. The MiniBAT® is a small platform suitable for one or two small instrument packages. Its size and weight allow deployment from watercraft as small as 6 m in length and by as few as two experienced personnel. The MiniBAT® is constructed from stainless steel and consists of a dive plane (the wing), a frame in which instrumentation is mounted, a stabilizing fin assembly, and a remotely controlled servomotor that varies the angle of the dive plane. A 50-m Kevlar cable containing eight electrical lines was employed as both tether for towing and electronic control cable. The Mini-BAT® is manufactured as a single configuration, but the cable is available in a variety of custom lengths.

Acquisition of several positional parameters is required for both automated and manual operation of the MiniBAT®, and for subsequent data processing:
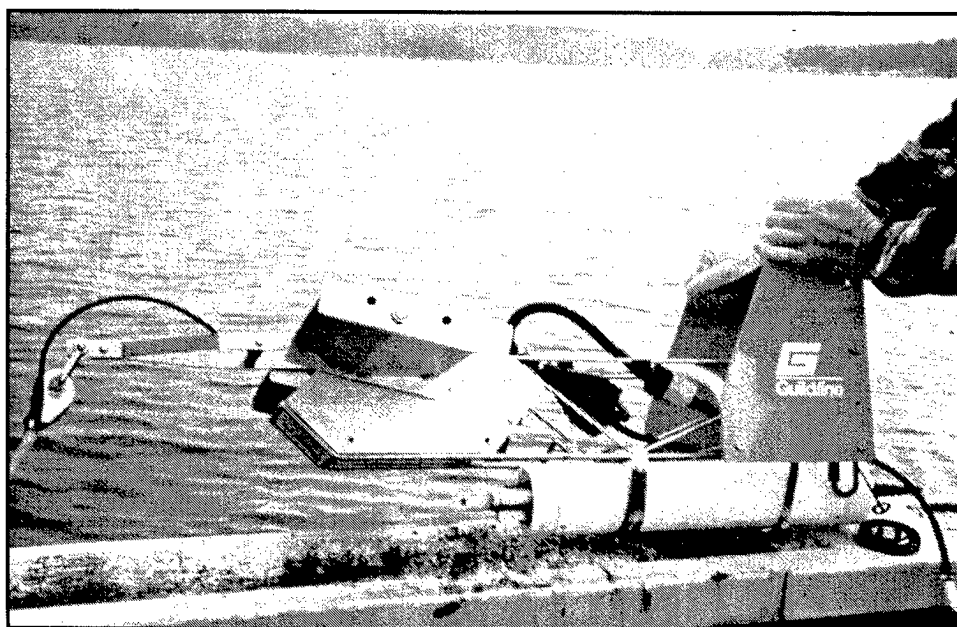
- Bottom depth
- Depth of towed platform

Figure 6.   The Guildline MiniBAT® with Hydrolab water quality sonde attached

- Depth of sonde
- Cable length (distance behind tow boat)
- Latitude and longitude
- Time/date

This information is acquired automatically using integrated GPS and hydroacoustic depth sensing equipment onboard the tow boat. GPS time is used as the time standard for all instrumentation, and the length of the cable is used to calculate the "setback" or actual distance of the towed platform behind the boat. Software supplied by the manufacturer (Guildline Instruments, Inc., 1999) allows water depth, depth of the platform, and GPS position to be continuously logged using a notebook computer. The same program also controls the operation and position of the MiniBAT®, and graphically displays its progress in relation to the lake surface and bottom. A commercially available Apelco marine GPS unit with integral depth sounding capability was interfaced with the Mini-BAT® controls and the computer software (Raytheon Electronics 1998). However, electronic designs change quickly, and selection of appropriate instruments requires care. For this application, the manufacturer recommended a specific unit. However, other units from other manufacturers may be compatible off the shelf. They must be capable of the following:

- Output of data string conforming to NMEA183 specifications
- Accurate GPS position measurement (this could include differential GPS)
- Accurate depth measurement

These requirements were needed specifically for the MiniBAT® platform and Guildline's In-tow software package. Other towable platforms may have different requirements.

Although only four of the eight control lines in the cable were used by the MiniBAT® and its controls, this demonstration did not hard-wire the sonde to the remaining available control lines. Because the sonde is capable of internal logging, the decision was made to employ that capability, carefully matching the time base of both platforms to ensure accurate association of the two databases. This arrangement eliminated the need for more than one notebook computer during the deployment.

For this demonstration the MiniBAT® was deployed manually from a 7.6-m MonArk boat powered by a 150-hp outboard motor. Because of the research nature of this demonstration, three personnel were employed during deployments: a boat pilot for the watercraft, a computer control operator, and a cable deployment person. In practice, and once the proper configuration of this system has been determined, the control operator should also be able to deploy the cable manually. As an alternative, a slip-ring-equipped manual winch for the Kevlar cable is available at extra cost and should lengthen the life of the cable as well as increase the ease of deployment. This option is also available from the manufacturer.

The procedure for each deployment involved locating a suitably large and relatively wide area of the lake, then releasing the assembly from the moving (1.5-2.6 m/sec (3-5 knots)) boat while carefully unspooling the cable astern. Once the maximum cable length was reached, the terminated end was secured to a cleat near the stern. Towing was attempted at speeds varying from 1.5 to 5.4 m/sec (3 to 10 knots). However, best results were attained at speeds of 1.5-2.6 m/sec (3-5 knots).

The software employed to control the position of the towed platform in the water column is capable of allowing manual or automated vertical position control. The computer displays a graphical view of the track of the platform as its vertical position varies with forward motion. The computer display also contains control buttons available for real-time adjustment of vertical position or the automated parameters.

The automated control features of the software were employed during this demonstration. To achieve proper descent and ascent behavior of the towed platform, the program parameters were custom adjusted for the Mini-BAT® configuration. Moreover, the MiniBAT® was configured through careful application of trial-and-error adjustments to optimize the balance of the load and provide the desired towing behavior. For the purpose of this demonstration, the goals were to control the vertical position of the towed platform in the water column and to allow automated vertical motion (undulation).

New or modified sensor packages or changes to the study depths require careful testing of the configuration prior to deployment to ensure proper towing behavior. Once determined, however, the system behavior can be faithfully reproduced under similar conditions. Forward velocity is also an important component of performance as is the manner in which the boat responds to the pilot. It is anticipated that each boat/platform/sonde system will require extensive testing to identify the best working configuration.

Water Quality Data Collection

Sensor choices

Field application of this technology depends on successful operation of two main components of the system. First the vehicle with associated controls and positioning capability must be operational and controllable. Second there must be successful operation of measurement hardware that is attached to the vehicle. Both components must be operational to meet demands for spatial data in three dimensions.

The simplest sensor technology that can be applied to this approach must be capable of measuring at least one limnologically relevant parameter and be capable of continuous data logging. An example of such

technology would include any of the numerous inexpensive thermal logging devices now available. The most complex devices that are small enough to be carried by the towable platform include multiparameter sondes available from several manufacturers. This study employed sondes from two manufacturers.

Preliminary evaluations of the performance of the MiniBAT® when transporting a payload employed a Hydrolab water quality sonde (Hydrolab Corporation, Austin, TX). However, a YSI model 6920 multiparameter sonde (YSI, Inc., Yellow Springs, OH) was selected for the data collection demonstration since it offered an expanded suite of water quality sensors in a compact configuration. The parameters that were measured included the following:

- Time/date
- Depth
- Temperature
- Dissolved oxygen concentration
- pH
- Specific conductance
- Chlorophyll fluorescence

With the exception of dissolved oxygen and chlorophyll fluorescence, the sensors on this sonde were of conventional design. The dissolved oxygen probe used a design that is proprietary to YSI. Instead of the conventional continuous polarographic electrode, this design employs a pulsed technology with predicted longer life for the electrode. The probe for chlorophyll fluorescence was also a YSI design but incorporated conventional features of other fluorescence measuring devices, including a blue light-emitting diode as an excitation source and a solid-state photodetector designed to preferentially detect the longer wavelengths associated with the in vivo fluorescence of chlorophyll.

The sonde was programmed for internal logging for these demonstrations using a notebook computer and software provided by the manufacturer (YSI, Inc., 1999). All parameters were programmed to log at 1-sec intervals, and options for data averaging or smoothing (e.g., running average) were disabled on the assumption that raw data would better enable analysis of the final data set. Once programmed, the sonde was mounted inside the frame of the MiniBAT® using cable ties to prevent vibration and a stainless quicklink to secure it in the frame. The MiniBAT®-sonde system was then checked onboard for signal continuity and control of the dive plane, then deployed overboard for the actual data collection.

One very important factor in deploying multiparameter sondes with a variety of sensor technologies is the variable ability of these sensors to respond to rapidly changing conditions. Although this study employed the latest sonde technology, analysis of results (explained later in this report)

showed that response time was a great limitation to the application of this approach. Great care must be taken to know the response times of sensors for various water quality parameters and to form expectations that are appropriate within those limitations.

Because the sonde was programmed to log internally, the software interface for observing real-time water quality data was not employed. Following retrieval of the MiniBAT®/sonde assembly, the sonde was removed and downloaded using software supplied by the manufacturer (YSI, Inc., 1999). Once downloaded, the water quality data logged during the deployment were available for analysis or display using the same software. This graphical display simultaneously plotted all parameters as a time-series. This was useful for quick identification of trends that may need further examination or for identification of depths or locations requiring additional deployments. The data were also exported in coma-delimited format allowing importation to other databases or statistical software packages. This was the procedure that was also used in the time-series data collection depicted in Figure 1.

As mentioned previously, integration of data from GPS and multiparameter sondes is important for analysis of spatial trends. The two methods of accomplishing this include delayed integration and real-time integration. Real-time integration of position and water quality data is the ultimate capability of this technology. Appropriate modification and preparation of the measurement hardware can allow seamless integration and production of a single data set with all parameters of choice immediately accessible for analysis. As mentioned previously, this is the most powerful application of the technology but the most intensive and expensive. For most applications, the alternative involving a delay may be adequate.

Delayed integration retains all of the data quality of the real-time alternative. The only feature that is lost with the delay is the real-time feature of the survey. If the need for instantaneous access to the integrated data is great, then that approach is appropriate. However, for most questions, it is sufficient to integrate the two components at a later time. But there are precautions to minimize error, detailed in a later section of this report.

Application and deployment strategies

Two basic strategies are appropriate for deploying the platform-sonde system: level flight, during which the system is maintained at a single depth, and undulating flight, for which the system is programmed to ascend and descend between preselected depths. In both cases, the deploying vessel can follow multiple transects (lateral or longitudinal) or predetermined courses designed to cover a specific region of interest adequately.

Data collected using the constant-depth approach specifically allow characterization of a single depth. For example, if the depth of an interflow or the metalimnetic zone is known, the towed platform could easily be

used to collect data describing the spatial extent or variation within the depth stratum. The towed platform could also be used in this manner to follow a tracer known to occupy a certain depth stratum. Application of this type is not more different, in principle, than any other previously known methodology capable of produce two-dimensional surface characterizations. The minor difference is that the two-dimensional characterization is made available to any desired depth and is no longer confined to the lake surface or near the surface.

Undulating flight of the towed platform-sonde system allows depthwise data collection. Navigating a single transect (either lateral or longitudinal) would produce a two-dimensional snapshot of water quality along the axis of that transect or path of travel. Combining information obtained from two or more transects offers the opportunity to display data three dimensionally. It should be noted that a depth-specific subsampling of the data also allows identification of data collected at the same depth.

Field evaluations of the towed platform-sonde system followed two sample design strategies during demonstration deployments: varying or undulating the MiniBAT® between upper and lower depth limits (a vertical range of approximately 25 m) along a longitudinal track that followed the thalweg of the reservoir; and undulating flight with repeated lateral transects throughout a region of the lake for the collection of data in three dimensions. Both strategies have potential application for a variety of limnological investigations.

Data management

Application of this technology generates large quantities of multiparameter data, and because it is possible to repeat a survey several times during one day, careful management of data sets is essential. Every precaution must be taken to ensure that collected data are entered into a data management system immediately following completion of surveys. Because data are spatially referenced and extremely time sensitive, even small time errors (a few seconds) can cause great errors in the location of water quality measurements. If the towed platform is in an undulating mode, these location errors are also manifested as serious errors in depth placement. Great care must be taken to reference time and position correctly to interpret data successfully during the analysis phase.

Two data logging configurations for the towed platform-sonde system are currently available. First, the control software and position data are logged on a real-time basis into an onboard computer. In addition, it is also possible to connect the measurement sonde directly to the same onboard computer. In this configuration both data collection processes occur simultaneously, and with additional interfacing, the system can be operated in an automatic manner, merging water quality and control and position data into a single data file. This approach is technically challenging but

Chapter 3   Technological Solution to Three-Dimensional Data Needs

possible, and it avoids some potential errors of the second approach, discussed in the following paragraph.

The second approach, as used for this demonstration, involves separate data collection efforts (i.e., independent logging of control and position data and water quality data) and the merging of resulting data sets during the data management phase. In this approach, the sonde acts as the second data collection platform, and its clock is set to match the time given for the GPS system. The second data collection platform is the onboard computer that logs control and position data. Each of the two platforms can export a file that is in a format capable of importation to database and statistical software. Time for each of the two data sets is used to match water quality data with control and position data. Because there is redundant measurement of depth (MiniBAT® control and sonde), the two measurements serve as an independent check on this data merging procedure, since depths should also match at each time increment.

The redundancy provides several advantages over the completely integrated approach. First, failure of control systems does not automatically eliminate useful data collection. Such a failure would limit only that collection and return operation to a more conventional sampling mode. In addition, the redundancy provides additional internal quality control capability that is mentioned in the previous paragraph. Most importantly, it allows flexibility of application of field equipment that may be in limited supply. If a sonde is modified to be hard-wired into the towed platform system, then it will be unavailable for any other application without great effort. In addition, maintenance and repair to that unit would be made difficult unless even more modifications were incorporated to provide plug-in capability. For most field applications in reservoirs, the labor and expense of such modifications may not be justified by the convenience of use.

4   Practical Use

The fully automated approach also is associated with some practical deployment risks that, although common to both approaches, are maximum in the automated approach. The use of a towable platform that manually or automatically travels through large depth ranges requires knowledge of the lake basin in which it is used. To avoid submerged obstacles, a safety feature was built into the control software for the MiniBAT®. This feature detects the depth of the bottom and provides automatic avoidance within a user-specified range of the lake bottom.

Impact of towable platforms with submerged objects is undesirable because of the risk of loss of all instrumentation and measurement capability associated with the towed package until the package can be repaired or replaced. Automatic avoidance of submerged objects, furthermore, is not foolproof as was demonstrated in this study on two occasions. Each instance was instructive, however, and they are described in the following paragraphs.

On the first occasion, the MiniBAT® was flown in an undulating pattern along the submerged channel of J. Strom Thurmond Lake, Georgia, while the depth was constantly monitored. Because there was a 50-m margin of error (based on the setback distance) in which the MiniBAT® could be flown toward the surface, the automatic bottom avoidance setting was allowed to control its path. On this first instance, the MiniBAT® impacted a sudden rise in elevation (submerged hill) because it could not respond quickly enough. Therefore, abrupt changes in elevation or the presence of large objects such as submerged bridges or other structures pose great hazards to the safety of the towed platform and the instrumentation carried on it.

On the second occasion, automatic flight was interrupted by a failure in the signal being transmitted from the MiniBAT®. Because the control program could no longer "see" the towed package, it could not know that a collision was imminent. Manual override of this condition failed, and the package again impacted a submerged hill in the impoundment.

On neither occasion was there damage to the equipment other than minor bends in some metal parts. The minor damage was easily repaired, and the platform was quickly returned to its fully functional condition.

Indeed, the strength of the Kevlar signal cable was impressive as a 3,629-kg (8,000-lb) research vessel traveling at 2 m/sec (4 knots) was stopped in its path by the impact. Such risk must be avoided and can be by carefully scouting the anticipated survey area for such obstacles and planning ahead to avoid them. In Richard B. Russell Lake, a known bridge was easily avoided by surfacing the towed package prior to passing the structure, followed by diving it back to operational depth.

GPS Postprocessing

Determination of position using GPS has advanced greatly in recent years. However, concerns for certain types of signal failure or error remain, and the manufacturer of the system should be consulted to determine the real limitations of the instrument being used. GPS instrumentation requires multiple satellite contact for best position determination. Any topographical or structural feature that blocks this contact will diminish the ability to determine position. This condition occurs, for example, in mountainous areas or in close proximity to large bridges or dams. In addition, power generation equipment may also be a factor. Although this instrumentation has greatly improved, such factors as multipath or other sources of errors that occurred in the past must also be addressed for best use today. Because the ability to compensate is specific for each instrument model, the final determination of its accuracy in each application must be performed by the operator for each application. In this study, GPS instrumentation was used as recommended by the manufacturer of the Mini-BAT®. This ensured data compatibility with the other connected instrumentation and with the software interface supplied with the towable platform.

Geographic position, bottom depth, depth of towed platform, and time/date were contained in a file created by the software supplied by the towed platform manufacturer. These data can be used to create plots for display of the tow history or exported to a database for further analysis. However, there is intentional error in the position data that must be corrected through postprocessing. The process is relatively simple and consists of downloading the position data for a fixed "community base station" and then subtracting the variance for the community base station. Postprocessing the data in this manner will ensure increased position accuracy.

In addition, there are modifications of this technology that increase positional accuracy through other types of correction. Differential GPS employs a second positional site and can be linked in a real-time manner to provide greatly increased accuracy without postprocessing. Other systems may use an additional commercial GPS reference to provide very fine scale accuracy, and these systems are often available through paid subscription to the service. The technology of determining position is constantly improving, and decisions on investment in hardware must judge future enhancements or costs against present needs.

Other Hardware Guidance

The type of boat, the choice of water quality sonde, the length of the cable, and the means of deployment from the boat are all important considerations. It is not recommended that a towed platform be deployed from a small craft. This demonstration employed a 7.6-m, metal-hulled boat with a cabin and 150-hp motor. While this boat was more than adequate for demonstration trials, this experience indicates that the deployment could have been equally successful using a boat as small as 5.0-5.5 m in length. The mass of the hull and the power of the engine will be the pri·ary factors contributing to a successful deployment. If deployment is ·complished manually, sufficient deck space for proper handling of the cable will be required. The Kevlar cable is very strong but can be damaged if twisted or kinked while supporting the load of a towed platform.

While large craft may be employed for this purpose, there is an obvious limit to the practical size needed. Furthermore, speed is not a concern other than being able to maintain a stable forward velocity of 1.5-2 m/sec (3-4 knots). A greater concern is for the computational instrumentation and the operational environment. Adequate space is important for manual handling of the cable, and an enclosed environment is desired for the onboard computer. Because the operator of the towable platform must pay careful attention to its performance at all times, some means of darkening the work area so that the computer screen can be seen easily is also desired.

The size and weight of the water quality sonde are important factors influencing vehicle performance. The first deployment of a towable platform should not include an additional payload. Once the platform is balanced and its operation practiced without an attached sonde, a variety of configurations can be tested for performance and stability. Initial trials showed that a heavy sonde tended to unbalance the towed platform and influence controllability. Successful deployment eventually required inclusion of buoyancy compensation in the form of flotation attached to the sonde to render the sonde neutrally buoyant.

The simplest configuration consists of the towable platform with a small device that adds hardly any mass or hydraulic resistance. This configuration will differ very little from the empty platform by itself. At the other extreme, a large, heavy sonde with additional attachments that may interrupt the flow may be difficult to balance. In this study, buoyancy compensation was needed and incorporated by attaching a measured piece of wet-suit material around the sonde itself. Neutral buoyancy was determined empirically by placing this combination into the water and observing its behavior. Once secured inside the MiniBAT®, this configuration worked well, and the sonde/platform combination performed in a manner similar to the empty platform alone.

The point of attachment for the tow cable was also a factor in this study. For all trials, the point of attachment was at the farthest forward position on the MiniBAT®. Subsequent communications with the manufacturer indicated that a position even farther forward was desirable and that new attachment holes could be drilled for this modification. Such modification would enable slower ascents and descents during undulating flight.

Cable length is specified during the construction of the towed platform and is determined by the maximum depth desired during deployment. Longer cables can still be towed at shallow depths but are a cost consideration. This demonstration employed a 50-m cable that was sufficient to carry the platform to depths of over 40 m, although most data were collected from depths less than 30 m. If no depth greater than 20 m, for example, is anticipated, then a cable of 25 m could be specified with substantial cost savings.

The towed platform was deployed from the stern on one side of the boat. Although a more balanced position would have been from the center of the stern, the side position avoided interference of the cable with the outboard engine. Once in the water, the platform was kept in motion during all phases of deployment, including during release and retrieval, to maintain vertical position.

Control surfaces and initial settings are important for the initial deployment of the empty towable platform, and the configuration of the towed platform with payload is critical for successful deployment. Care must be taken to ensure that once at depth, the platform can successfully return to the surface. The importance of this ability must not be minimized! A single uncontrollable dive in shallow water or in waters containing obstructions can be catastrophic.

Trials for each new configuration are necessary to optimize the relative positions of all control surfaces including the main dive plane and the angle of the stabilizing fins. Approximately one full day was required during this study to optimize these settings by trial and error. Once the physical configuration is set, the automated control settings can be optimized based on the requirements of the study. There was not a single systematic procedure for determining these settings.

While optimization of the physical configuration and automated controls of the vehicle were essential for successful operation, additional considerations were identified during this demonstration trial. The angle of descent of the towed platform tended to be steeper than that of its ascent. The potential hazards resulting from unexpectedly rapid dives, particularly in shallower waters, are obvious. This effect, while disconcerting initially, was partially controlled by careful configuration of the dive plane angles, the sonde balance, and the control settings. An additional means to control this problem is to set the angle of stabilizing fins to minimize the tendency to dive or to vary the attachment point of the tow cable, thus affecting the balance.

5 Performance of Towed Instrumentation

Setup Procedure for Towed Platforms

The initial configuration of the MiniBAT® or similar towable platforms should be determined by the manufacturer. This configuration should be as conservative as possible allowing for minimal vertical mobility and minimal chance for mishap. The towed package is best deployed for the first time with little or no load attached. This allows the new operators to concentrate on learning the system and how the platform tends to behave with no load. By incrementally adding and changing loading on the towed platform, operators can identify the loading factors to which the platform is most sensitive.

One procedural sequence is as follows:

- Assemble all components on shore (or in the laboratory) to test the electronic connections.
- Test the data acquisition and control programs using operational equipment.
- Test the controls of the towable platform to ensure expected mobility of control surfaces.
- Test their motion to ensure complete range of movement.
- Be certain that program indicators agree with the actual motion of the control surfaces.
- Set trim to neutral configuration and main controls to upward (ascending) configuration.
- Repeat these steps on the tow watercraft.
- If these steps are successful, then under forward motion, carefully deploy the towable vehicle without payload.
- If the towable vehicle displays predicted behavior (stays on surface), finish full deployment of cable.

- Observe the vehicle at the surface, slowing or increasing the speed to note its response to changes in velocity. Enough velocity should be maintained to keep the vehicle at the surface.
- Carefully change the controls to less ascending and greater downward angle.
- Note the angle at which the vehicle begins to descend to depth and return the angle upward to note its response.
- If the platform refuses to return, stop the watercraft and manually return the platform to the surface (this should not be necessary unless there is a serious problem). Serious conditions may include a tendency to dive very steeply and rapidly with no return response, an instability in which the platform flips over and is dragged backwards (or other wrong position), or any erratic behavior that is not expected.
- If the platform returns, the first successful deployment has been completed and additional modifications may be made.
- These modifications may include attaching the sonde, varying the trim planes, changing the tow attachment point, etc. These modifications should be attempted one at a time to ensure understanding of their effect.
- Finally, sophisticated changes to the control program may be made to customize the path of flight or to maximize stability at certain depths.

To repeat the warning regarding submerged obstacles, and to familiarize system response to such obstacles, the operator should attempt a drill in which an imaginary object is observed and quick response is needed. Honest assessment of the ability to avoid such imaginary objects will help ensure avoidance of real ones. When the operator gains sufficient confidence, such a drill can be applied to a known object (using great care and without the sonde aboard). At all times, conservative operation is recommended whereby the operator carefully monitors bottom depths and the behavior of the towed platform, ready to override the controls manually and bring the unit to the surface if necessary. The control software and hardware both allow this capability.

After the operating parameters have been identified, other factors such as forward velocity can also affect the behavior of the system. In this study, greater velocity made the towed platform less stable. Programmed increases in depth proceeded with disproportionately greater rates of change in depth, and the programmed maxima and minima for depth tended to be overshot under greater forward velocity. Rapid changes in depth were detrimental to water quality measurements using instruments with slow response times (see "Water Quality").

Control software contained a number of adjustable parameters that modified the rate of change for ascending and descending functions. The relationship between some of these parameters is not intuitive, but much of the

control is available by modifying just a few of the most important parameters, particularly the upper and lower depth limits. Some control is possible through management of boat speed, although below a critical velocity (approximately 1.5 m/sec (3 knots)) the towed platform did not respond. The demonstration data were gathered at speeds of approximately 2 m/sec (4 knots).

As expected for hydrodynamic systems, beyond some limit the behavior of the system was unstable. This instability was manifested as excessively steep ascents and descents. In extreme conditions, system instability concluded with the towed vehicle becoming inverted with complete loss of control. Greater stability seemed to be gained by attaching the tether closer to the front of the towed platform.

Under normal operation, the descents to greater depths tended to occur more quickly than ascents to the shallower depth limit. Figure 7 displays data collected using an optimized configuration with specified depth limits of 5 and 20 m. Figure 7 is a time-series plot of towed platform depth. Assuming constant velocity, distance could be substituted for the time axis. Ideal behavior would have been represented by a sinusoidal pattern exactly meeting the 5- and 20-m depth limits. As shown in the lower plot of Figure 7, the control program depth limits were approximately met although they were usually exceeded or overshot. This tendency was more severe if the forward speed of the watercraft was increased without some compensating modifications to the control program. Figure 7 also shows that the descent to greater depth occurred at a rate nearly twice as great as the ascent to the shallower depth. This important factor greatly affected data analysis.

Except under very controlled forward velocities, a constant depth for the towed platform was difficult. Constant depth was more easily maintained for shallower depths owing to the steeper tow angle if the platform was at a greater depth. Constant depth was relatively easy to achieve either automatically or manually for depths to 15 m and at speeds of approximately 1.5-2 m/sec (3-4 knots).

Water Quality

Evaluations of sensor response to changing water quality conditions were conducted in J. Strom Thurmond Lake. Data collected from a stationary boat on the previous day using traditional profiling techniques were compared with those collected near the same location using the MiniBAT®-sonde system. Resultant profile data for selected variables and corresponding data collected during both ascending and descending movements of the MiniBAT®-sonde system are presented in Figure 8. It should be noted that profile data for chlorophyll concentration were not collected.
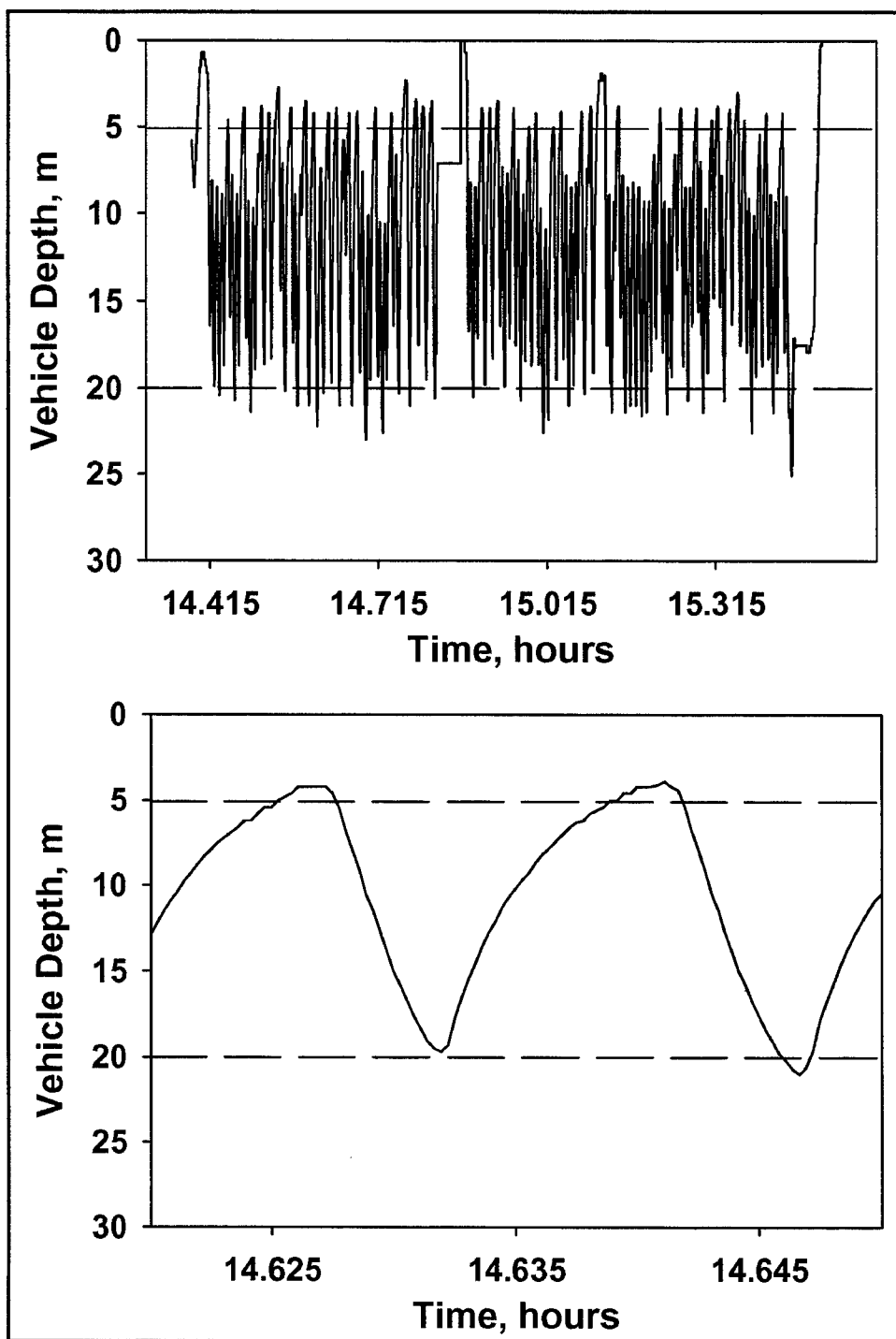
Figure 7.   Changes in vehicle depth during a 1-hr deployment of the MiniBAT® in
J. Strom Thurmond Lake (upper). Changes in vehicle depth are also
displayed on an expanded scale (lower) during two cycles of ascent
and descent. Ascending and descending rates averaged 0.53 m/sec
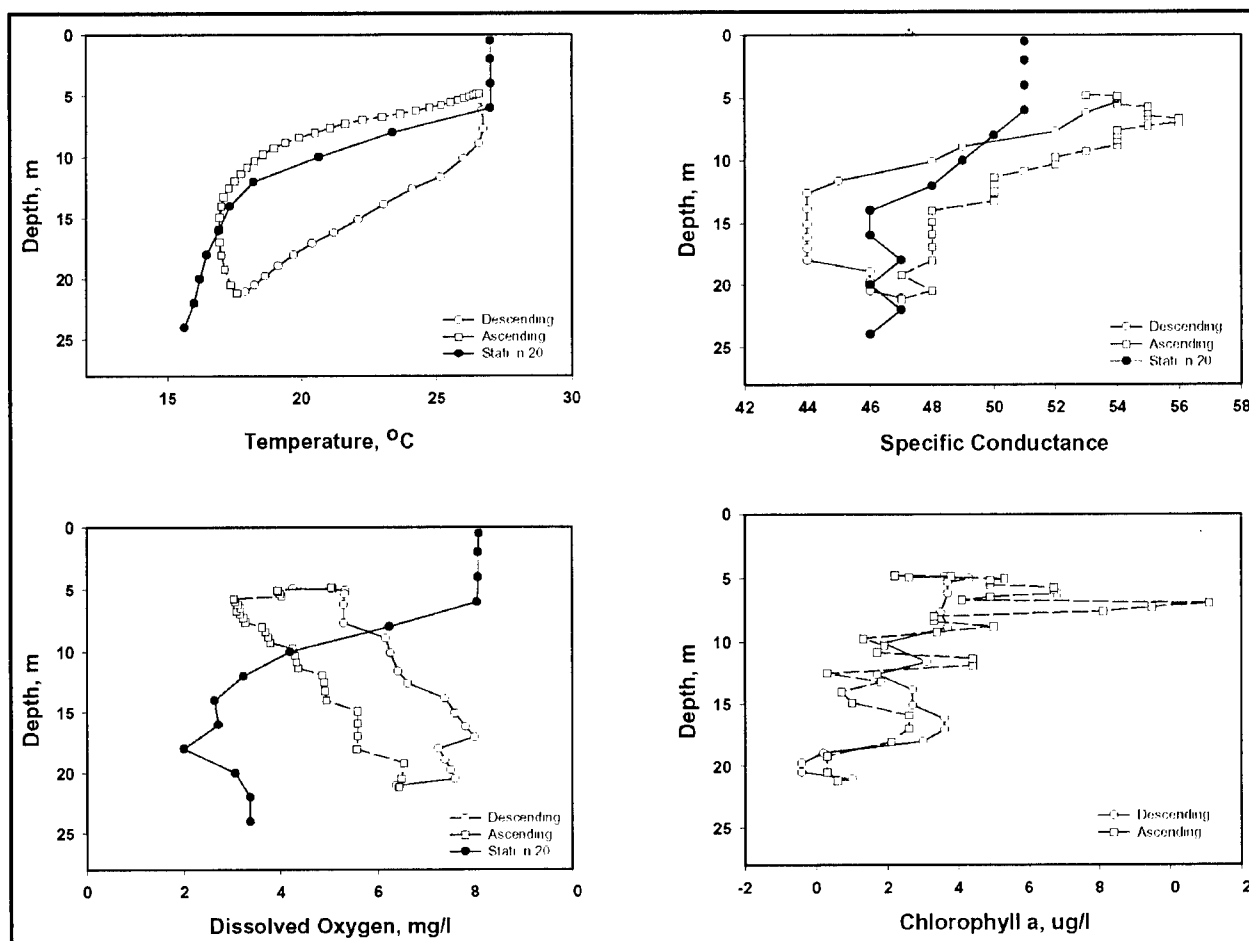and 0.92 m/sec, respectively

Figure 8. Correspondence between temperature (upper left), specific conductance (upper right), dissolved oxygen (lower left), and chlorophyll concentration (lower right) measured in profile at sta 20 in J. Strom Thurmond Lake and using the YSI sonde towed on the Guildline MiniBAT® in the vicinity of sta 20. Profile data for chlorophyll concentration were not collected

The temperature sensor responded relatively rapidly with changes in depth; however, the slower rate of ascent allowed more accurate estimates than those obtained during the more rapid descent. The result was a pronounced hysteretic effect (Figure 8). Differences between the ascending estimates and profile data may reflect temporal changes or be due to the averaging of temperatures over short depth intervals due to the ascending movement of the sonde.

The specific conductance sensor responded rapidly to changing conditions and is well-suited to the towed platform approach to water quality studies (Figure 8). It is reasonable to conclude that the principle of the measurement of specific conductance and the fact that specific conductance is not highly variable resulted in the close correspondence with the profile data. While there are clear differences between data collected during descending and ascending data, both are within ± 2 µS of the profile value. This is within the range of variability commonly observed for such instruments.

There was limited correspondence between values of dissolved oxygen concentration measured during profile sampling and those obtained by the MiniBAT®-sonde system on either ascent or descent (Figure 8). The slow response of the dissolved oxygen probe was clearly a severe limitation to the collection of accurate data in rapidly changing environments. The rate at which the towed platform moved between regions of differing dissolved oxygen concentration far exceeded the rate at which the sensor could respond. Current technology in the design of dissolved oxygen sensors does not provide a sufficiently rapid response for such applications. To compensate for this lack of rapid response, either much slower rates of change in depth or tows at constant depth must be employed if accurate descriptions of water quality conditions are to be obtained. In situations requiring dissolved oxygen characteristics in three dimensions, the towed platform can still be useful but its rate of undulation would have to be greatly decreased. However, multiple tows at different depths may provide the best approach to data collection in such situations.

The nature of the limitation of the dissolved oxygen sensor arises from two sources. First, few sondes actually log or report dissolved oxygen measurements at 1-sec intervals. Most wait 4-10 sec for each update. Other than redesigning sonde technology, there is no solution to this. The other source for the limitation is the electrode technology itself. Nearly all dissolved oxygen electrodes currently employ some type of polarographic or Clark electrode design. All of these require a gas permeable membrane through which oxygen diffuses at a rate dependent on the membrane material, membrane thickness, and concentration gradient. Current water quality sonde design incorporates dissolved oxygen sensors that cannot respond quickly enough to follow rapidly changing gradients. In conventional surveys, this is controlled by leaving the electrode in contact with a parcel of water long enough to attain a steady state across the membrane at which time the stable measurement is recorded. This is not a feasible technology for the towable platform. Unless a new quick-responding sensor design is incorporated into water quality sondes, dissolved oxygen will remain an intractable parameter for this method.

Chlorophyll fluorescence could not be compared to profile data since the latter data were not collected. Alternatively, ascending and descending data were compared as a means to assess sensor performance under the assumption of similarity between both types of data. While considerable variability was exhibited, there was strong correspondence between consecutive ascending and descending fluorescence profiles (Figure 8). A rapid response would be anticipated since optical sensors do not require a period of equilibration.

The conclusion for most of the data comparisons is that although the towed platform is capable of rapid ascent and descent, its performance is capable of exceeding the capacity of water quality sensors to respond rapidly enough. This is particularly true for dissolved oxygen sensors. Chlorophyll fluorescence, conductivity, and depth responded most quickly. These parameters could reliably respond to rapid changes in water quality

conditions. Temperature measurement technology exists for which short time constants would allow rapid response to changing conditions. Such improvements are feasible now and would allow complete application of this approach to field studies.

Other physically based measurements such as depth (pressure) and optical measurements (such as fluorescence) also respond quickly and can be applied now. Simple measurement of electrical resistance (conductivity) is equally ready for contemporary application. All other sensor technologies that require equilibrium conditions across a membrane or a chemical reaction are limited in their application. This approach could be used successfully to address trophic status in three dimensions but could not be easily applied to habitat as determined by dissolved oxygen requirements.

6 Example Applications

Longitudinal Transect in Two Dimensions

The first demonstration application of the MiniBAT®-sonde system was conducted in Richard B. Russell Lake. Deployment involved towing the system along a longitudinal transect extending from the forebay to a location approximately 9 km upstream (Figure 9). The transect closely followed the thalweg although the flexibility of the approach would have allowed a more circuitous route if necessary. Traversing the transect resulted in the collection of over 50 ascending profiles and required approximately 1 hr. Based on prior experiences, the same duration of effort would have allowed traditional profile data collection at only three discrete locations.
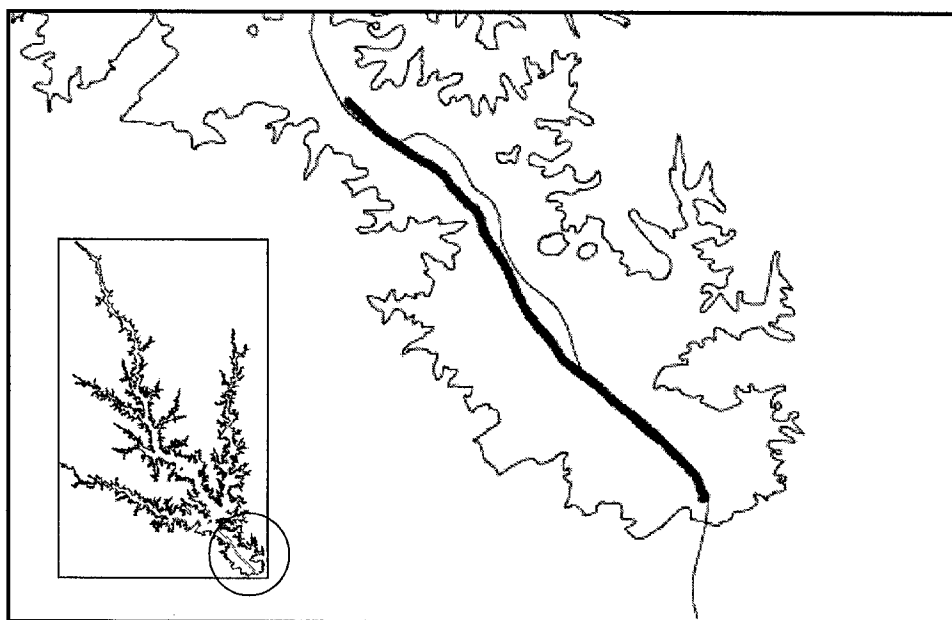

Figure 9. Longitudinal transect (bold line) along the thalweg (thin line) in the downstream reach of Richard B. Russell Lake. Locations based on GPS navigational information

Data collected during this study illustrated the potential advantages of the approach. Temperature and chlorophyll concentrations were "mapped" by interpolation of observations collected during the deployment using contouring program Surfer (Golden Software, Inc., 1995). As was noted previously, to reduce errors associated with slow sensor responses during descent, only data for periods of ascent were used. The data allowed depthwise description of the thermocline and associated concentrations of chlorophyll along the transect (Figure 10).

Lateral Transects in Three Dimensions

The utility of the MiniBAT®-sonde system for collection of three-dimensional water quality data was demonstrated in the forebay of J. Strom Thurmond Lake. The sample design involved the establishment of a series of lateral transects (Figure 11) and undulating movement by the MiniBAT®-sonde system. Automatic depth control was selected for the purposes of the demonstration and the shallower nearshore or littoral zone areas were not included.

Resultant data were subsampled by 1-m depth strata for ease of analysis using Surfer. The depth ranges were selected to provide adequate data density. In Figure 12 the various interpolated estimates of the data distributions are displayed. In this example, clear trends in the spatial (both vertical and horizontal) distribution of chlorophyll fluorescence were observed. While the results are limited to a visual comparison, there is marked correspondence in the locations of the chlorophyll maxima between depth strata indicating a degree of internal consistency assessment. These data document the occurrence of important water quality trends in this region of the lake. These include pronounced vertical stratification and horizontal heterogeneity of phytoplankton communities.

Data Manipulations

The generalized approach for data management has been discussed earlier in the report. However, the fact that data are not arranged in concise depthwise arrays poses an interpretive challenge. For this study, all lines of data were maintained intact as a raw database. For comparison, however, decisions on how to subsample these data were necessary to provide packets of spatially similar data to be grouped and used to calculate variances. This problem still demands new ways to analyze such data sets.

In this study, the data were arbitrarily grouped in 1-m depth intervals as displayed in Figure 12. Complete analysis of such data should, in fact, also consider similar groupings in other spatial dimensions. This study chose to employ a conventional view of such results and elected to separate strata
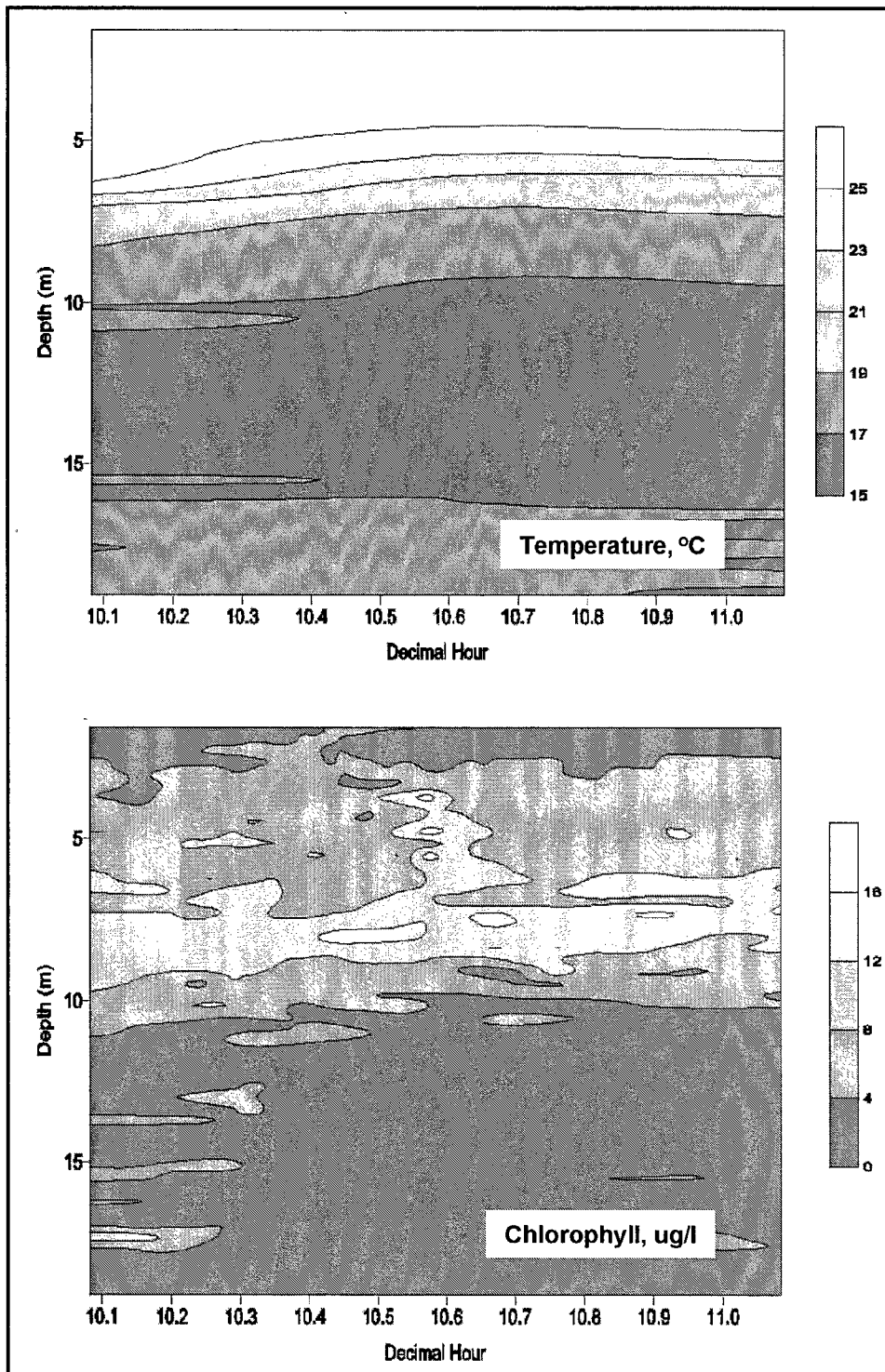
Figure 10. Depth distribution of temperature and chlorophyll concentration along a longitudinal transect in the downstream reach of Richard B. Russell Lake
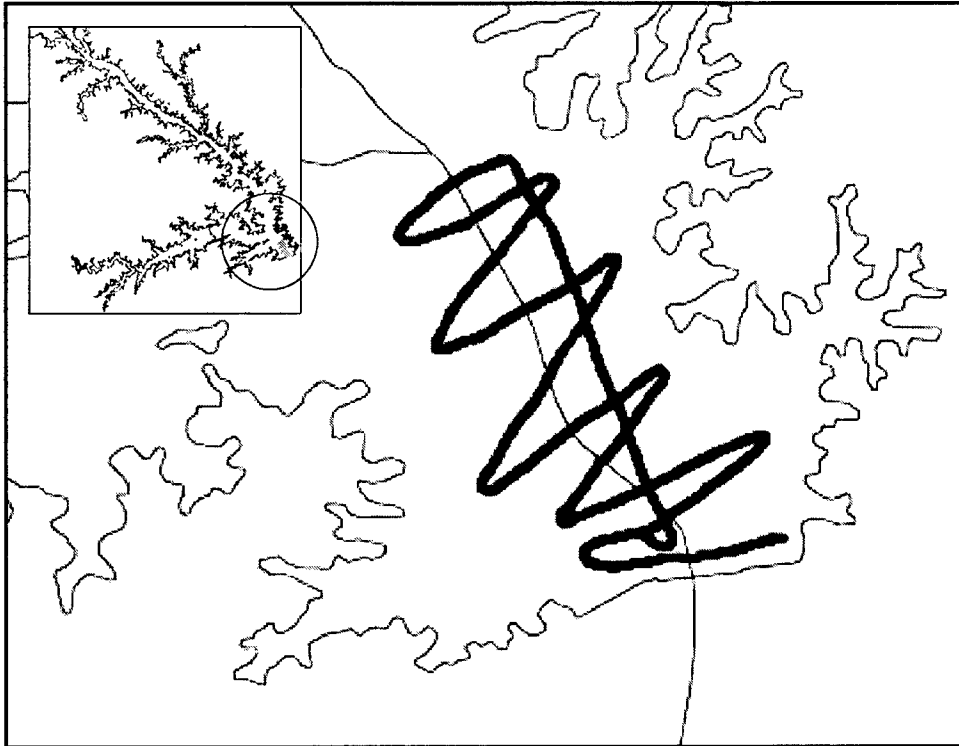
Figure 11. Lateral transects (bold line) in the downstream reach of J. Strom Thurmond Lake. Locations based on GPS navigational information

by depth. The resulting images shown in Figure 12 represent the patterns of variation in the other two dimensions for each depth stratum.

Because this approach is not mature in its application, patterns of variation should also be sought in all other dimensions, perhaps even seeking the dimension of maximum variation. Such analytical designs are feasible, and they may be very instructive in their interpretation of lake water quality trends in the future.

At this time methods are limited to interpolation, graphical display, and pattern recognition that were developed for two dimensions. Tools available for such analysis were used in this study. Surfer is a powerful graphical program that allows visual manipulation of data as shown here. Other similar programs also offer similar advantages.

At this time, subsampling by depth remains a good starting approach for analysis of trends, patterns, statistical differences, etc. This is especially true because in most stratified lakes, depth is likely to be the dimension containing the strongest gradients. And once subsampled, the data are available for conventional methods of trend or pattern analysis.
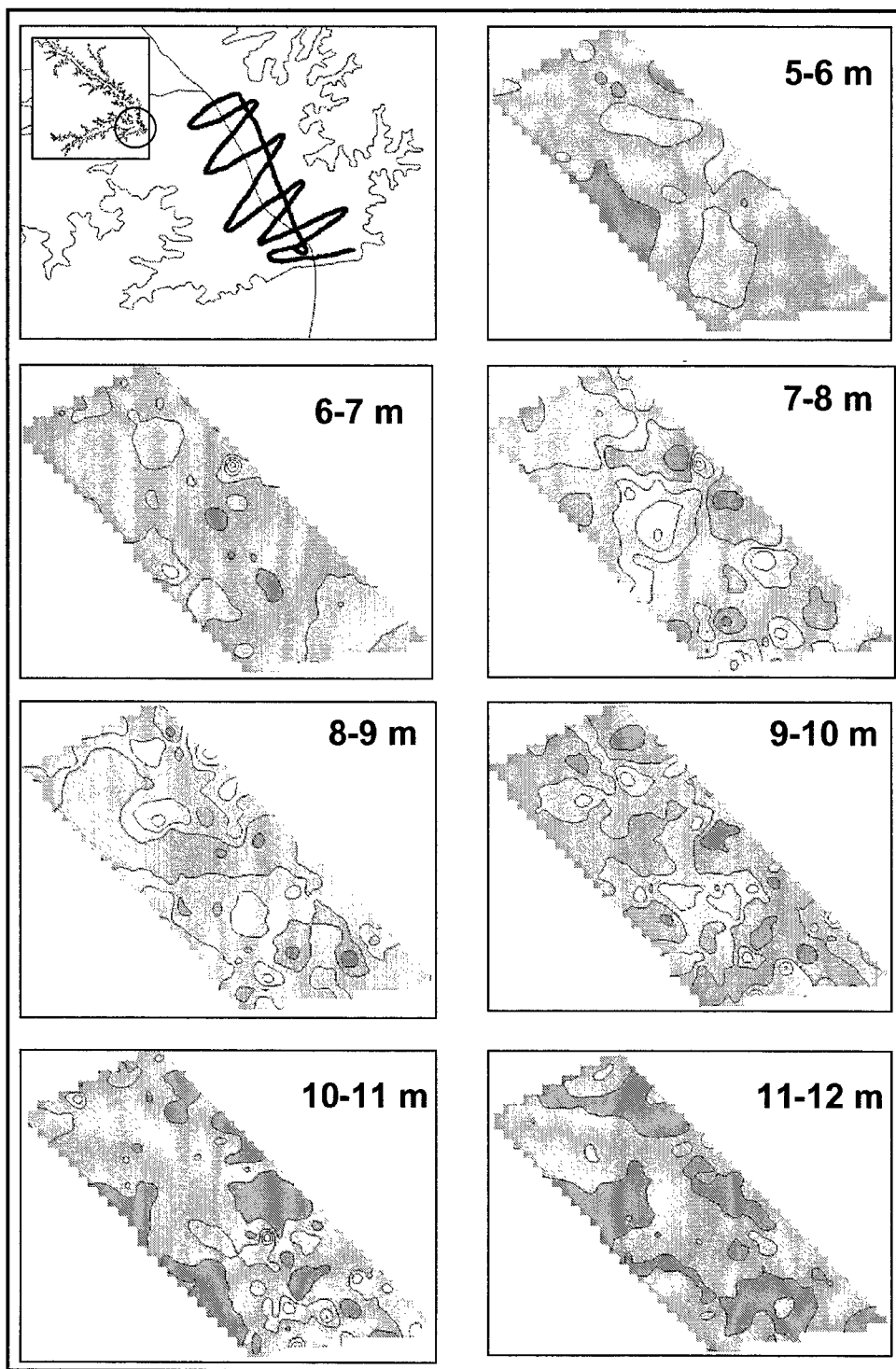
Figure 12. Navigational track on J. Strom Thurmond Lake (upper left) and the distributions of integrated chlorophyll concentrations for depth ranges

7 Conclusions

The new ability to collect water quality data rapidly in two and three dimensions presents opportunities and challenges for conventional measurement technology and data analysis and interpretation. The ability to collect data rapidly and to vary collection sites rapidly over multiple dimensions is a reality. Trials with the MiniBAT® were successful in a variety of operational modes. Automated and manual undulating position control was possible when the platform was loaded with a conventional water quality multiparameter sonde. However, the ability of conventional sensor technology to respond to this capability is variable.

Sensors that respond quickly to gradients were best suited for this approach to field studies. These include conductivity, depth, fluorescence, and in a limited way, temperature. Other sensors could not respond quickly enough to provide useful data using this approach. These unsuccessful sensors included pH and dissolved oxygen and will likely include any other sensor that requires equilibration across a membrane or a chemical reaction. New sensor technology is needed to make such parameters tractable with this field sampling approach.

The application of this capability is likewise limited to large reservoirs, which experience complex water quality gradients. Smaller lakes and reservoirs as well as those constrained by narrow channels may offer limited opportunity to apply this new field approach. However, even in a narrow channel, the towable platform offers the advantage of enabling more rapid and intense measurement of field water quality characteristics in two dimensions.

Data management of the results of such studies is complicated by the need to incorporate both spatial data and water quality data from different data sources. The challenge also includes the ability to analyze the results using methods intended for conventional surveys and data in two dimensions. Although judicious subsampling can produce useable data sets for analysis using conventional methods, new methods must be developed to address the demands of multiple dimensions.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Aquatic systems exhibit complex temporal and spatial heterogeneities, which are poorly described using traditional sampling strategies. Technological advances in instrumentation now offer new opportunities for the collection of fine-scaled, spatially explicit water quality data for lakes, reservoirs, and rivers. Described here are practical considerations for developing and applying strategies employing Global Positioning Systems (GPS), multiparameter sondes, and towed submersible vehicles. Equipment and sample design approaches are demonstrated based on example applications. Limitations and potential advantages are discussed.

14. SUBJECT TERMS

Chlorophyll	GPS	Temperature
Conductance	MiniBAT®	Towed vehicle
Dissolved oxygen	Reservoir	Water quality
Global Positioning System	Sampling	

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